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Topographic changes due to the 2008 Mw 7.9 Wenchuan earthquake as revealed by the differential DEM method

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ABSTRACT

Landscape evolution in active orogenic regions is inevitably affected by the repeated strong earthquakes triggered by the corresponding active faults. However, the lack of adequate methods for the documentation and monitoring of mountain-building processes has resulted in a shortage of quantitative estimates of orogenic and eroded volumes. A strong earthquake and its associated co-seismic landslides represent a sudden pulse in landscape evolution in tectonically active areas. The 2008 Mw 7.9 Wenchuan earthquake dramatically modified the topography of the Longmen Shan region. Based on topographic data before the earthquake and stereo pairs of post-earthquake remote sensing imagery, we derived pre- and post-earthquake DEMs (digital elevation models) of the three regions along the Longmen Shan Thrust Belt. By comparing the geomorphic features before and after the earthquake, we find that the Wenchuan earthquake smoothed the steep relief and caused a co-seismic uplift of the Longmen Shan region. The medium-relief regions increased; however, the high-relief regions decreased, indicating that the local relief is controlled by repeated strong earthquakes. The changed slope aspect indicates that the formation and modification of the east- and west-facing slopes are controlled by tectonic events in the Longmen Shan region, which might be associated with the regional stress field. However, the unchanged aspects of other slopes might be controlled by long-term erosion rather than tectonic events. The topographic changes, landslide volume and co-seismic uplift indicate that the greatest seismically induced denudation occurred in association with a thrust faulting mechanism and low-angle fault geometry. Our findings reveal that the local relief has been shaped by the localized, seismically induced high rate of denudation within the plateau margins, and that the formation of local relief is also related to tectonic events, especially the events that have occurred on low-angle faults. This study also indicates that the multi-temporal DEM differential method is valuable in detecting seismically induced topographic change.

1. Introduction

Whether tectonic processes control climatic change and whether climatically driven denudation/erosion at the earth's surface can govern tectonic processes have been the subjects of considerable debate (Molnar and England, 1990; Avouac and Burov, 1996; Willett, 1999; Beaumont et al., 2001). However, the differences in the temporal and spatial scales of mountain-building and climate processes complicate the study of the interactions between these processes. Landscapes in tectonically active areas also continuously evolve due to the complex combined effects of crustal motion, erosion and deposition (Burbank and Anderson, 2011). The Tibetan Plateau has long been recognized as an ideal location for studies of the interactions between climate and tectonics. The large-scale short- and long-term erosion rates on the Tibetan Plateau suggest high denudation rates focused on a 50–70 km wide zone along the plateau margins (Lave and Avouac, 2001; Burbank et al., 2003; Thiede et al., 2004; Garzanti et al., 2007; Liu-Zeng et al., 2011). However, at detailed spatial and temporal scales, the pattern and mechanisms underlying the seismically induced denudation and co-seismic uplifting on and around the Tibetan Plateau are still poorly known, especially within the plateau margins. Quantifying the spatial and temporal patterns of seismically induced denudation/erosion and uplift is important for understanding the role of strong earthquakes and denudation/erosion processes in shaping the topography. The occurrence of the 2008 Mw 7.9 Wenchuan earthquake provides a rare opportunity to quantitatively study seismically induced topographic change.

It has been widely accepted that the high mountains and plateaus were built by large dip-slip or oblique-slip earthquakes (Avouac, 2008). Recently, Parker et al. (2011) challenged this widely held notion using a quantitative comparison of the co-seismic uplift and landslide

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material produced by the 2008 Mw 7.9 Wenchuan earthquake. They note that the mass wasting induced by strong earthquakes should be taken into consideration when describing orogenic growth processes. Changes in the topography and the interactions between deep crustal processes and mass removal are complex and remain controversial. The landslide volume derived from the area–volume equation is much larger than that estimated based on the moment magnitude (Keefer, 1994; Malamud et al., 2004; Parker et al., 2011), which may indicate large uncertainties in area–volume statistical estimates. Furthermore, a simple comparison of the statistically derived landslide volume and the co-seismic uplift does not provide details on the seismically induced topographic changes, such as the spatial distribution of these changes.

Recently, high-resolution and multi-temporal DEMs (digital elevation models) have proven valuable in monitoring geomorphic, co-seismic and volcanic surface deformations (Arrowsmith and Zielke, 2009; Zielke et al., 2010; Burbank and Anderson, 2011; Zhang et al., 2011; Oskin et al., 2012; Zielke and Arrowsmith, 2012). To estimate the contribution of earthquake-triggered landslides to erosion and to identify patterns of landscape evolution with seismic activity, co-seismic topographic changes need to be quantified using pre- and post-earthquake differential DEMs. By analyzing the slope angle, roughness, aspect and elevation change between the pre- and post-earthquake DEMs, we analyze topographic changes due to the Wenchuan earthquake.

2. Tectonic setting

The Longmen Shan region, one of the steepest tectonic and topographic margins of the Tibetan Plateau, is marked by a 5000 m decrease in elevation within the 50 km from the inter-plateau to the lowland Sichuan Basin (Fig. 1; Burchfiel et al., 1995; Chen and Wilson, 1996). The topography in the Longmen Shan region has developed with little crustal shortening and with low slip rates along the major fault systems, as revealed by continuous GPS observation (King et al., 1997; Chen et al., 2000; Zhang et al., 2004; Gan et al., 2007) and the geological slip rates (Densmore et al., 2007; Zhou et al., 2007). The Longmen Shan Thrust Belt consists of four major fault systems formed in response to the orogenic growth of this margin: the Wenchuan-Maowen, Yingxiu-Beichuan, Guanxian-Anxian and Qingchuan fault systems (Burchfiel et al., 1995; Kirby et al., 2002; Jia et al., 2006; Densmore et al., 2007; Burchfiel et al., 2008; Kirby et al., 2008). The latter three systems ruptured during the 2008 Wenchuan earthquake (Lin et al., 2009; Liu-Zeng et al., 2009; Xu et al., 2009a,b; Lin et al., 2012). The co-seismic deformations reveal that the Longmen Shan Thrust Belt is the main convergent boundary between the Tibetan Plateau and Sichuan Basin and possesses a right-lateral strike-slip component (Lin et al., 2009; Liu-Zeng et al., 2009; Xu et al., 2009a,b; Zhang et al., 2010; Lin et al., 2012). Numerous co-seismic landslides were triggered on the steep slopes in this region (e.g., Xu et al., 2009a,b; Ren and Lin, 2010; Yin et al., 2010; Dai et al., 2011a,b; Parker et al., 2011; Tang et al., 2011; Huang and Fan, 2013), changing the local topography. After an earthquake, landslide materials generate sustained high sediment flux rates above normal levels (Keefer, 1994; Malamud et al., 2004; Larsen et al., 2010; Parker et al., 2011); subsequently erosion rates gradually return to pre-earthquake levels (Godard et al., 2010; Hovius et al., 2011). In the Longmen Shan region, earthquake-triggered deformations can dominate local erosion and landscape evolution, as occurs in other mountainous regions in the world (Hovius et al., 2011; Mackey and Roering, 2011).

3. DEM derivation and elevation error analyses

3.1. DEM derivation

Most of the quantitative topographic analyses in this paper are based on comparisons of high-resolution pre- and post-earthquake DEMs. Chen et al. (2006) have shown that the differential DEM method is effective in detecting topographic change caused by co-seismic landslides. They used multiple-scale and multiple-source DEMs to derive the topographic change resulting from the Tsaoling landslide that was induced by the 1999 Chi-Chi earthquake; they found that the errors arising from the use of different DEM scales and sources are acceptable in studies of landslide-scale topographic change. Therefore, in the present study, due to the data limitations in the Wenchuan earthquake epicentral region, the 25-m-resolution pre-earthquake DEM was derived from digital 1:50,000 topographic maps, which were surveyed using stereo pairs of aerial photographs with sufficient ground control points (GCPs) by the National Administration of Surveying, Mapping and Geoinformation of China in the 1970s. The DEM constitutes the best pre-earthquake topographic data for comparison with the 90-m-resolution SRTM DEM and the 30-m-resolution ASTER GDEM because high-resolution stereo pairs of remote sensing images were not captured before the Wenchuan earthquake. Stereo pairs of remote sensing images were used to derive the post-earthquake DEM. The Indian Remote Sensing Satellite P5 (IRS-P5) was launched on May 5, 2005, and carried two state-of-the-art panchromatic cameras (PAN fore and PAN after). The stereoscopic imagery data have a 2.5-m spatial resolution in the visible region of the electromagnetic spectrum, which facilitates the generation of accurate three-dimensional maps. In this study, the IRS-P5 imagery was used to derive a 5-m resolution DEM. Three representative sites (I–III) with almost no cloud coverage were selected for the DEM derivation; the data timeframe includes the three weeks after the 2008 Wenchuan earthquake, from May 12 through June 3, 2008. To improve the quality of the post-earthquake DEM, we also applied a field survey of ground control points using Trimble R8 GPS units (Fig. 1). To obtain sufficient precession, we observed for at least 15 min at each location, with a continuous reference station within a 50 km range. Using PixelGrid software, we derived the DEM using a semi-automatic algorithm based on the GCP points, the rational polynomial coefficient (RPC) camera model (Tao and Hu, 2001) and the tie points between the PAN fore and PAN after imagery.

3.2. Elevation error analyses

The elevation error of the pre-earthquake DEM was analyzed by comparing it with the continuous GPS stations in the Longmen Shan region, which are a part of the Crustal Movement Observation Network of China (CMONOC I) and the Tectonic and Environmental Observation Network of Mainland China (CMONOC II). We obtained 24 h of continuous observation from 14 GPS stations within the study area from October 8 to October 9, 2007. The measurement error for the 24 h continuous GPS observation is within several millimeters. The mean elevation error of the pre-earthquake DEM (Table 1) was ± 4.1 m, and the median was ± 3.6 m; the latter is more appropriate in describing the level of elevation error (Bohm and Zech, 2010) because we do not know whether the error is symmetrically distributed. Because the post-earthquake GPS data are classified, no continuous GPS data were obtained. Consequently, the elevation error of the post-earthquake DEM was calculated by comparing the DEM with field GPS observations spanning approximately 30 min at 12 ground control points. The GPS error of the ~30-min observation is less than several centimeters. The mean of the elevation error values of the post-earthquake DEM (Table 2) was estimated to be ± 1.5 m, and the median was estimated to be ± 1.2 m. Thus, the precision is sufficient for measuring landslide volumes by subtracting the pre-earthquake DEM from the post-earthquake DEM within the landslide area.

4. Topographic analysis

4.1. Slope angle and roughness

Most landslides occur in areas with steep slopes (Burbank et al., 1996; Densmore et al., 1998; Dai and Lee, 2002), suggesting the